THE QUEST FOR BETTER

Susan Hubbard and Yoram Rubin

Water is a key control on the health of plants. Recent studies have shown that careful irrigation management can have beneficial effects on many crops, including almonds, citrus, plums, pistachios and wine grapes. Such management is especially important in water-scarce regions that have a large agricultural industry. California, for example, is one of the nation's most productive farm states, producing 50 percent of the nation's fruits, nuts and vegetables on more than 8.8 million acres of farmland. With 80 percent of the state's developed water being used through irrigation for agriculture, California uses more water than any other state in the nation.

The planet's explosive population growth and competing needs for water will contribute to major water conflicts in the coming years. Smart water management thus can have a particularly significant impact in dry agricultural regions that have high-value cash crops, such as in some wine-grape-growing areas of California and Australia.

TRADITIONAL APPROACHES

Through trial and error and over hundreds of years, French winemakers have recognized that certain areas within vineyards produce finer wines than others. Wines made from the same kind of grapes that are grown in the same region, using identical farming procedures, which are harvested at the same time and made into wine in exactly the same way, can be dramatically different. Some wines may be dryer or more astringent than others, and the color intensity and aromas may vary. Soils play a significant role in such "terroir" (see story, page 20).

Due to natural geological processes, soil properties can vary laterally over distances as small as several meters. Recognition of these small-scale variations within a vineyard or portion of a vineyard can lead to premium wines that reflect the terroir of the area. The historical perspective that has helped define terroir in traditional wine-grape- growing areas, however, is absent in newer winemaking areas, such as California and Australia. Thus, New World farms still face the challenge of mapping their soil properties in detail.

Wine grape growers generally accept that moderate water stress on grapevines early in the growing season has a positive impact on grape quality. Irrigation approaches can provide grapevines the necessary water when it is not naturally available from rainfall (see story, page 36). Understanding when and how much water to apply is critical for optimized wine grape production in areas that rely on irrigation.

Soil parameters influence the depth at which vine roots grow and the amount of water held within the vine root zone. For

ER WINE USING GEOPHYSICS

Wine grapes need just the right amount of water stress early in the growing season. Analyzing soil variations at a vineyard can help managers understand when and how much water to apply for optimized wine-grape production in areas that rely on irrigation.

Courtesy of the Wine Institute

Precision viticulture may significantly improve profits for a winery by lowering the risk of reduced quality of wine grapes.

example, sandy areas, due to their relatively large grain size, have a low water-holding capacity, whereas soils with higher clay content have a higher water-holding capacity. As a result, grapevine roots that are located within shallow clay-rich soils will often tend to have more available water than those roots that tap into sand-rich soils, which allow naturally present or irrigation water to drain more rapidly. These natural soil variations over short distances often hinder the ability of a vineyard manager to irrigate a vineyard uniformly and obtain the same vegetation and fruit characteristics. Because the amount of irrigation water that a plant requires is a function of the plant and soil characteristics as well as climate, irrigation approaches often are guided by measurements of these properties.

When vineyard managers suspect that water stress is critical, they will often collect plant measurements at “spot” locations across a subset of the farm; these measurements typically provide lagging indications of a plant’s level of water stress. Similarly, climate-based methods have been useful for developing irrigation schemes using meteorological data representative of a larger spatial scale. These models, however, cannot account for the smaller-scale variabilities in grape quality associated with changes in soil properties. And while large-scale surveys, such as those provided by the U.S. Department of Agriculture’s (USDA) Soil Conservation Service, delineate general information about the spatial variations in soil properties, they do not provide the necessary level of detail required to make management decisions at the vineyard scale. Furthermore, the “industry standard” approach to vineyard soil characterization is to dig backhoe pits for soil-sample collections at points located on a 75-meter grid. Such sparse spacing is also typical when collecting traditional water-content measurements, such as from soil samples or boreholes.

The disparity between the typical spacing of standard soil measurements and the scale of natural soil variations creates challenges for vineyard managers, who want to develop a uniform and high-quality crop in spite of these variations. Fortunately for winemakers, however, new high-tech approaches are now being developed to map the spatial and temporal variability observed within a vineyard that have the potential to guide precision viticulture.

PRECISION TECHNIQUES

Rob Bramley of CSIRO Land and Water and the Cooperative Research Center for Viticulture in Australia has described how annual grape yields per acre can vary by a factor of 10 within a single vineyard. Bramley says that the patterns of spatial variation in yield typically stay constant over time, regardless of year-to-year variations in yield potential, which are driven largely by climate. Adapting farming practices (such as the volume and timing of irrigation and fertilization, or the timing of harvest) as a function of the natural variabilities has the potential to enable grapegrowers to deliver more uniform parcels of fruit to the winery. Such precision viticulture may significantly improve profits for a winery by lowering the risk of reduced quality of wine grapes.

Due to the potential premium, researchers are considering many high-tech approaches that can be used to better understand the smaller-scale spatial variations within a vineyard. Lee Johnson of the NASA Ames Research Center in California has described how multispectral remote-sensing data can be used to provide high-resolution estimates of the vineyard canopy, such as leaf area. These data have been useful, for example, to illustrate the variation in vegetation density. Near harvest time, vineyard managers can use such information to indicate which vines are ready to be picked.

Maps of soil texture and moisture could guide vineyard development and allow vineyard managers to plant grape varieties that prefer less moisture relative to other varieties in sandy soils, while concentrating varieties that prefer wetter conditions in more clay-rich soils. In vineyards that are already developed, maps of soil properties would be useful for guiding targeted irrigation strategies, which focus on delivering water to the grapevines only when and where it is necessary. Such approaches have the potential to increase crop quality while at the same time reducing water use.

PROBING BELOW GROUND

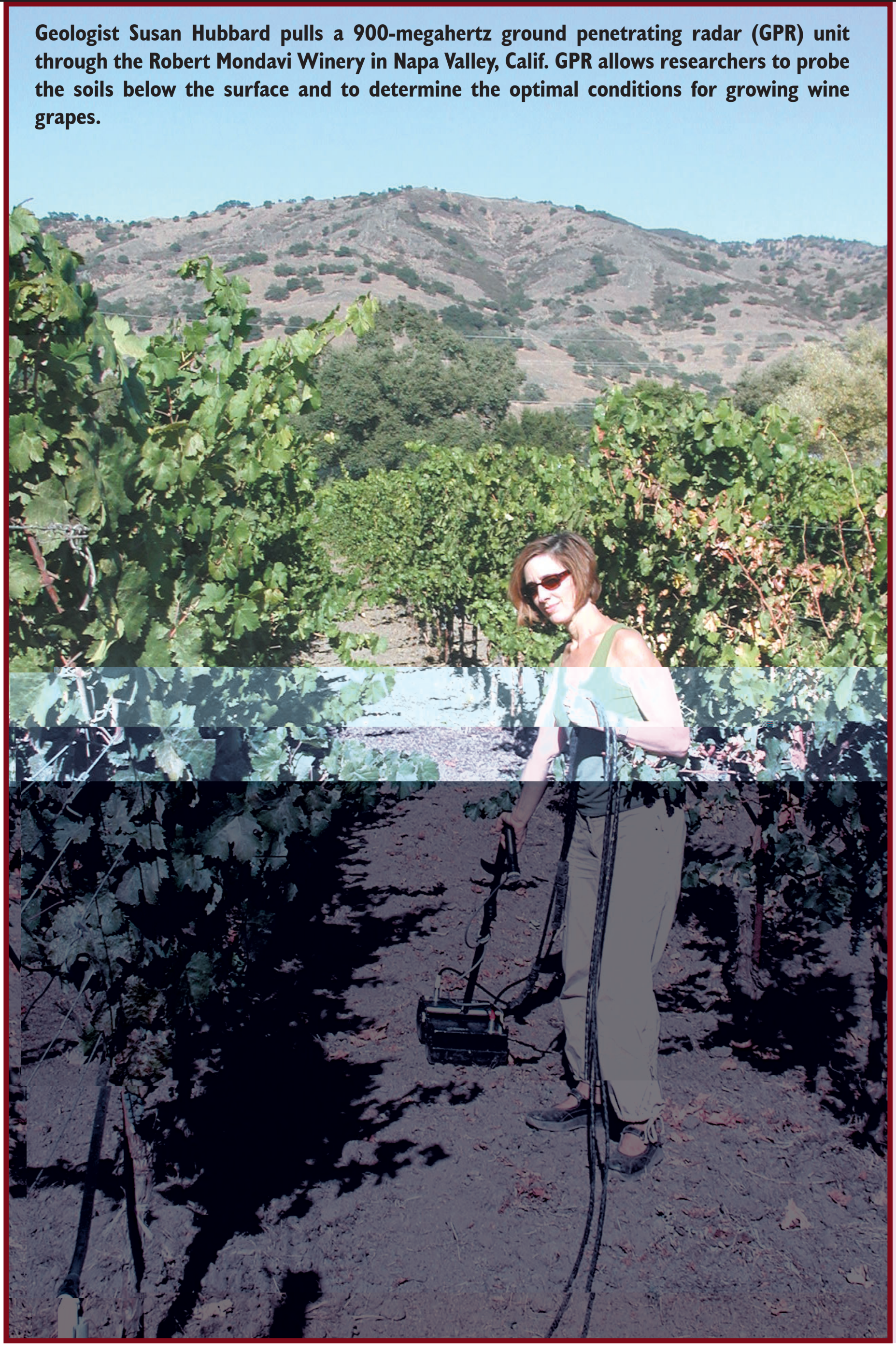
Surface geophysical tools can probe the subsurface with high spatial resolution and in a non-invasive manner, thus offering great potential as a tool for precision viticulture. Researchers have used surface electrical resistivity and electromagnetic methods in recent years to assist precision agriculture studies.

The ability to conduct electrical current through the soil is a function of a variety of factors, such as the clay content, water content and the concentration of salt in the soil. As such, unique interpretation of electrical conductivity data in terms of a single soil property can be challenging, although it has been successfully performed using site-specific controls and calibration.

Most recently, surface ground penetrating radar (GPR) approaches have been used to provide maps of soil water content within California vineyard sites. GPR uses high-frequency electromagnetic waves (about 100 megahertz to 1,000 megahertz) to probe the subsurface. The vacuum-cleaner-sized GPR unit sends an electromagnetic pulse into the soil as it is pulled along the ground surface (either manually or attached to farm equipment). Researchers can use the travel time of the electromagnetic wave that is sent into the ground to estimate the "dielectric constant" of the soil.

The dielectric constant of air is 1 and of water is 80; these two values represent the approximate end members of the dielectric constant range. The dielectric constant of dry soils is approximately 4 to 8. As the soil pore spaces become filled with water, the effective dielectric constant increases. Relationships have been developed to relate the dielectric constant values to water content. Thus, the velocity of the GPR signal can be converted into estimates of dielectric constant values and ultimately into water content.

Because GPR sends both groundwaves (shallow) and reflected waves (deep) into the soil column, these different signals can provide estimates of water content at different soil depths. Our research team has used both GPR groundwave and reflection techniques at various frequencies to estimate soil water content distribution over time within two different California vineyards: the Robert Mondavi Winery in Napa County and the Dehlinger Winery in Sonoma County.



Geologist Susan Hubbard pulls a 900-megahertz ground penetrating radar (GPR) unit through the Robert Mondavi Winery in Napa Valley, Calif. GPR allows researchers to probe the soils below the surface and to determine the optimal conditions for growing wine grapes.

Courtesy of Susan Hubbard

The Robert Mondavi Winery. We tested the concept of using the GPR groundwave technique to estimate water content on soils at the Robert Mondavi Winery, which are categorized by USDA as Bale Loams. The approximately 3-acre study site is planted with Cabernet Sauvignon grapes. The topography and water table were fairly uniform within the study area, and all vines in the study area were subject to the same volume and frequency of irrigation water via a drip system during the warmest months (typically May through October).

Using 900-megahertz GPR groundwave velocity data, we estimated the electromagnetic velocity and subsequently the dielectric constant and water content throughout the study vineyard several times during the year. Volumetric water content obtained using this approach at Mondavi was very accurate, as recently described by Katherine Grote and colleagues in *Water Resources Research*. Their independent comparison of the Mondavi results with conventional soil-moisture measurements also revealed that the GPR method sam-

WINE'S DEEPER HISTORY

Jonathan Swinchatt examines alluvial fan sediments at the bottom of a hill in a winery in Napa Valley. Swinchatt and David Howell have recently classified alluvial fan sediments as one of three "earth process units" in which wine grapes can grow. They found that such sediments produce some of the best wines.

David Howell

Geologists David Howell and Jonathan Swinchatt were standing atop a hill overlooking a vineyard in Napa Valley one day, when David Jones, a geologist and winery owner, turned to them and said: "What you're tasting in a bottle of wine is a hundred million years of geologic history," recalls Howell of the U.S. Geological Survey in Menlo Park, Calif. This thought sent Howell and Swinchatt out into the vineyards to examine the underlying landscape that was shaping some of the world's greatest wines.

Winemakers and scientists alike have known that what makes good wine is a confluence of factors, including topography, climate and soils — known as "terroir." But the characteristics that constitute terroir are largely a reflection of today's landscape, Howell says, and the character of a wine has a much deeper history than that: a geologic history. "There is a saying that 'great wine begins with dirt,'" he says; however, in Napa Valley where the soils are young, great wine also begins with bedrock.

Napa Valley lies within the Coast Ranges of California, bounded on the east by the Sierra Nevadas and the Great Valley and the Pacific Ocean on the west. Napa Valley's geology and fertile farmland are a result of a long and complex series of volcanic and subduction events reaching back 140 million years. And because bedrock is at or near the surface of most of Napa Valley's vineyards and the soils are young by geologic standards (perhaps as young as 15,000 years), "it is important to know what type of structure you're working with," Howell says.

Thus, Howell and Swinchatt began to map out the geologic and topographic history of the valley. By overlaying existing soil maps with geologic maps, they created guides that provide a "new framework for examining the relationships between the ground and grape, place and quality," they write in their upcoming book, *The Winemaker's Dance*. To define characteristics fundamental to grape growing and the wine produced, Howell and Swinchatt devised "earth process units" or EPUs, three distinct provenances of soils.

Beyond the valley itself, most of the land in Napa is hilly, steep and dissected by streams. This land falls into the first EPU category, that of "residual materials," or thin layers of soil overlying bedrock. The soil that formed in place atop the bedrock is not well-developed, nutrients are sparse, and the grapevines are usually stressed. Wines grown on this land tend to be intensely flavored, highly concentrated and tannic, according to the authors.

In contrast, vineyards located on alluvial fans produce berrylike wine that is much softer in character than that from the mountains. So-called alluvial EPUs lie at the bottom of both mountain chains that line the edges of Napa Valley. The soils atop the alluvial fan materials were carried by streams down the mountain slopes, and may be thick or thin and composed of gravel, sand, silt and clay. Much of the rich history of Napa Valley wine has developed on alluvial EPUs, the authors say.

Fluvial EPUs occupy the remainder of the valley floor and are the thickest and richest of Napa sediments, Howell says, often to the detriment of vineyards. The thick vegetation that grows here gives wines a "prominent herbal" character. Few, if any, wines are produced solely from grapes grown on fluvial EPUs, Howell says.

Although Howell and Swinchatt's EPUs are specific to Napa Valley, "you could use this discrimination system anywhere," Howell says, especially in places where the soils are young. In places such as South Africa where the soils are very old, however, the soils would no longer retain much of the character of the bedrock. Thus the characteristics of the soil itself would be more important to analyze.

In any region, Howell says, taking a holistic approach to winemaking is key. Fortunately, many winemakers are coming to realize, he says, that "good wine comes from the earth, not the winery."

Megan Sever

pled the top 10 to 20 centimeters of the soil layer — an important zone for plant roots.

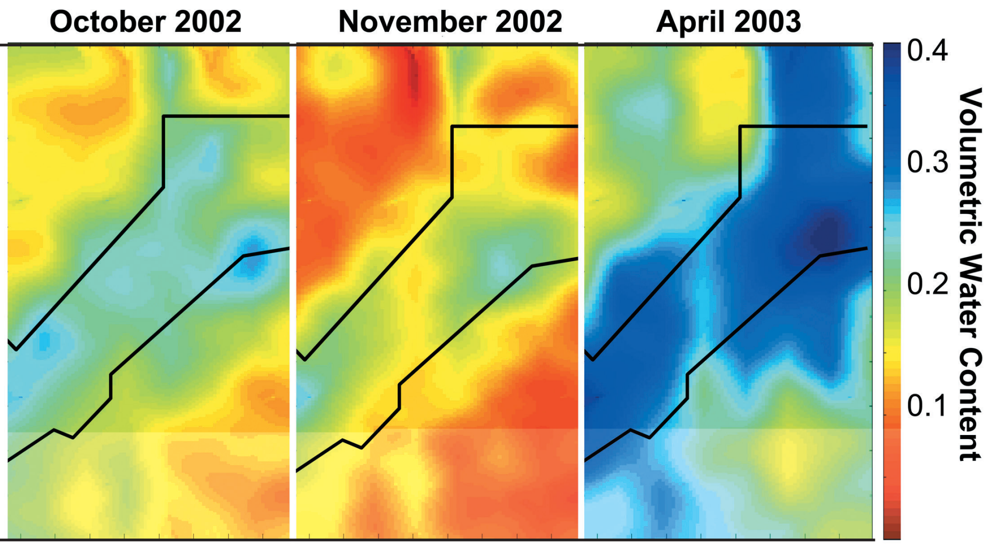
Because the measurements were recorded as the GPR unit was pulled through the vineyard at a spacing of 0.1 meters, the obtained soil-moisture maps provided extremely dense information — higher density than usual. Comparison of the water-content images and the soil-texture data at the site showed that soil texture controls both water drainage and spatial distribution of soil moisture. The sandy soils were consistently drier, whereas the more clay-rich soils were consistently wetter — thus revealing significant variations in shallow-soil properties within a single vineyard block.

The Dehlinger Winery. We tested the concept of using the GPR reflection approach to map deeper soil water content at the Dehlinger Winery. Soil textures at this site varied between sandy loam and clay loam. The crops in this study area are 20-year-old Chardonnay vines, all of which are derived from the same rootstock. No in-row tilling has been performed at this site (the natural geological layers are intact). An above-trellis spray system is infrequently used during hot weather.

The GPR reflection approach required information about the depth of the reflector from borehole measurements, making it more complicated than the groundwave approach that we used at the Mondavi vineyards. A GPR reflection occurs when there is a dielectric contrast between two subsurface units, such as a soil layer over bedrock and unsaturated soils and soils beneath the water table. In some soil environments, the soil layers exist in a gradational continuum, rather than as a series of distinct layers with detectable interfaces. However, as

MOISTURE MAPS

Researchers measured the average volumetric water content in the top 1 to 2 meters of soil over a 3-acre study block at the Dehlinger Winery in Sonoma County, Calif. Using 100-megahertz ground penetrating radar data, they found that the reflection surface took the shape of a buried channel across the study site. This channel-shaped feature has consistently higher water content and consistently lower grapevine vegetative growth, as revealed through both observations and these soil moisture maps. The low growth could be a response to water logging of the roots during the early stages of growth.



Courtesy of Susan Hubbard

different soil textures tend to have different soil water-holding capacities, juxtaposition of soil layers having different moisture content can potentially create enough of a dielectric constant to generate a GPR reflection.

We used the GPR reflection technique to image a key reflector surface at the Dehlinger site, which was located between 1 and 2 meters below the ground surface. The reflector surface took shape as a buried channel across the study site, which was consistently wetter than the surrounding area (see sidebar above). We collected GPR data at the site several times over a year. The soil moisture at the study site changed during the year due to natural meteorological conditions. As such, the dielectric constant of the soils changed, and the time that it took the signals to travel down to the key reflector and back also changed. We used the GPR reflection travel-time data to estimate the average water content of the soils above the mapped reflector several different times during the year.

As studied by Ian Lunt and colleagues, the estimates obtained from GPR reflections compared very favorably with those measurements obtained at a single well-bore location using conventional methods. However, the GPR data provided much more exhaustive information about the distribution of water content than what was obtained using the wellbore methods.

As was found at the Mondavi study site, the subsurface variations governed the water-content distribution consistently over time. The channel-shaped feature runs diagonally through the study site, and appears to greatly influence the soil water distribution. Marty Hedlund, Dehlinger's vineyard manager, has observed that the area outlined by the channel-shaped feature has consistently lower grapevine vegetative growth than the surrounding areas, from his monitoring of the fruit and pruning weight of the vines for many years. The correspondence of the soil moisture distribution and the vegetation variations at this site illustrates how soil variations may influence grapevine characteristics.

LOOKING FORWARD

Our experience within the Robert Mondavi and Dehlinger vineyards suggests that surface geophysical methods may be very useful for accurately mapping soil variations in very high resolution. The soil-moisture patterns, often governed by soil texture, remain the same through time, even though the soil moisture content fluctuates with irrigation and season. Thus, once researchers and winemakers identify patterns in the soil properties, they can develop an efficient layout of the vineyards that allows for uniform farming that still renders high-quality wine grapes. The work also suggests that point measurements at "hot spots" within the vineyard may suffice for subsequent water management purposes.

Use of such precision viticulture strategies will increase as the demand for water supplies increases. We envision taking a holistic approach — combining soil information (estimated using geophysical methods such as GPR), with remotely sensed canopy information and local climate data, to develop a better understanding of the relationships between soil, vegetation and meteorological variables. Lars Pierce of California State University at Monterey Bay has said that high-resolution information could ultimately be incorporated into a predictive model geared specifically toward vineyard managers. Such a model would allow vineyard managers to develop farming strategies simultaneously geared toward improving wine-grape quality and reducing water use.

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Precision farming strategies could help improve wine-grape quality and reduce water use at vineyards such as the Dehlinger Winery in Sonoma County, Calif., shown here.

Courtesy of Susan Hubbard